IEEE Transactions on Energy Conversion, Vol. 3, No. 3, September 1988

MODELING OF TRANSIENTS IN PERMANENT MAGNET GENERATORS WITH MULTIPLE DAMPING CIRCUITS USING THE NATURAL abc FRAME OF REFERENCE

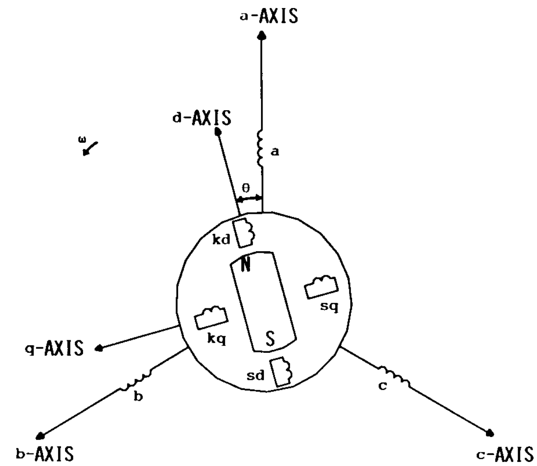
A. A. Arkadan, Student Member
N. A. Demerdash, Senior Member
Clarkson University
Potsdam, New York

Abstract - In this second of a set of two companion papers on the modeling of permanent magnet generators with multiple damping circuits, a computer-aided method to model their transient performance and determine their parameters, is presented. The method is based on the development and use of state models in the natural abc frame of reference, in which the abc machine winding parameters were determined from combined energy-current perturbation and finite element magnetic field computation methods. This is an advantage over other methods of simulation of machine transients that make use of models which are based on rotating frames of references (dq0 Park's transformation and associated models), in that effects of magnetic nonlinearities, space harmonics in the mmfs, and space harmonics in flux density waveforms as well as winding flux linkages on all machine parameters are readily and rigorously accounted for from 2-D field solutions. The method is applied to a two-pole, 75 KVA, 208V, 24000 r/min permanent magnet generator with multiple damping circuits, to study the effects of various generator faults on generator transient characteristics, starting from no-load and rated load initial conditions. Furthermore, the natural abc frame state models were utilized, in conjunction with the methods of IEEE Standard 115 in a unique approach to compute conventional dq0 frame steady state inductances, and subtransient inductances and time constants of the above mentioned permanent magnet generator. The model was used for further investigation of the design of the damping windings of the machine.

INTRODUCTION

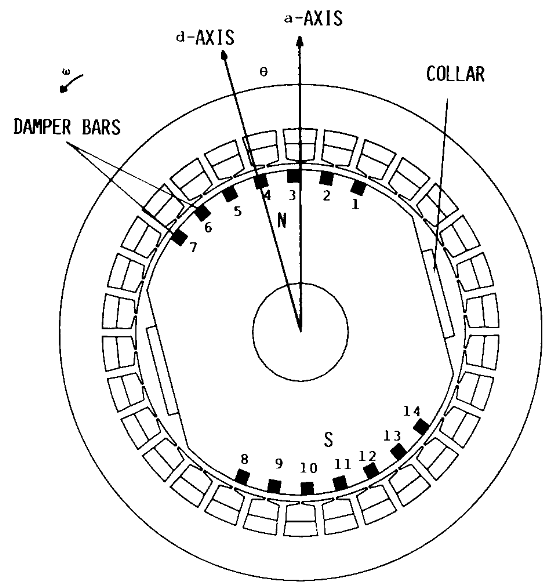
In this second of a set of two companion papers, a computer-aided method based on the utilization of a lumped parameter state model in the natural abc frame of reference, for simulation and prediction of transient characteristics of permanent magnet (PM) generators with multiple damper windings, is presented. The state model which was presented in the companion paper, reference [1], is used here to study the transient performance of a two-pole, 75 KVA, 208V, 24000 r/min permanent magnet (PM) generator with multiple damping circuits. Figure (1) shows the machine winding schematic diagram of this PM generator. The windings a, b, and c, represent the PM generator's armature housed in the stator slots shown in the machine cross-section of Figure (2). The two equivalent windings, kd and kq, shown in Figure (1), represent the damping effects of the rotor-mounted damper bars shown in Figure (2), along the direct and quadrature axes, respectively. Meanwhile, the two equivalent windings, sd and sq, depicted in Figure (1), represent the damping effect of the rotor-mounted metallic collar (damping ring) shown in cross-section in Figure (2), along the direct and quadrature axes, respectively.

88 WM 002-8 A paper recommended and approved tby the IEEE Rotating Machinery Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1988 Winter Meeting, New York, New York, January 31 - February 5, 1988. Manuscript submitted September 1, 1987; made available for printing November 25, 1987.



MACHINE WINDINGS SCHEMATIC DIAGRAM

Figure (1)



MACHINE CROSS-SECTION

Figure (2)

The permanent magnet generator winding parameters associated with this natural abc frame state model, were determined from a numerical approach using a combination of an energy-current perturbation method and finite element magnetic field solutions [2]. This was carried out at uniformly spaced rotor positions every six electrical degrees covering an entire 360 electrical degrees of a full ac cycle for each studied load. This process was detailed in the first of this set of two companion papers, see reference [1]. The resulting generator parameters enabled these authors to rigorously include the impact of magnetic circuit

0885-8969/88/0900-0722$01.00©1988 IEEE

nonlinearities and space harmonics due to stator slotting and rotor saliency, as well as armature loading and damping circuits' effects, on the transient performance of this PM generator. These considerations represent a significant advantage of this approach over other methods and state models, which are based on dq0 type rotating frames of reference and their associated inherently linear transformations, in which effects of space harmonics in the mmfs and flux linkages are necessarily neglected [3-5].

The response of this PM generator to sudden three phase short circuit faults, at different load conditions, was determined using this model as detailed below. From this transient fault analysis, the different computer simulated profiles (CSPs) of the transient currents of this PM generator were obtained. Furthermore, the state model was adjusted to study line to line (L-L) faults at different load conditions as given below.

Examination of the literature, a very limited example of which are references [3] through [5], reveals that the inclination to make use of the rotating dq0 frame of reference in the modeling of electric machinery is deep seated and well embedded in generator design and analysis methodologies. Hence, it is used extensively when studying the performance of such electric machinery. Accordingly, for the benefit of others who would rather use dq0 based models, this work was extended to obtain the PM generator's characteristic parameters in the dq0 frame of reference. These are parameters such as the steady state and subtransient inductances, and time constants of the PM generator at hand. Transient inductances cannot be properly defined for this PM generator because of the nonexistance of a conventional excitation field winding. The dq0 parameters were determined using the various computer simulated profiles (CSPs) of the transient currents resulting from simulation of short circuit faults by means of the developed abc frame of reference state models, in conjunction with application of the methods of IEEE Standard 115 [6], which are originally intended for laboratory determined transient current oscillograms, to these CSPs of the transient currents of the armature.

Comprehensive details of the transient fault analysis, as well as the extraction of the dq parameters of this 75 KVA PM generator are given below. Furthermore, a comparison of the values of these inductances with corresponding values determined from other methods of computation of direct and quadrature axis inductances is given. Finally, the impact of the addition of a shorted damping ring (damping collar) around the permanent magnet rotor on the values of the PM generator parameters and transient fault characteristics were investigated.

THE STATE MODEL OF THE PERMANENT MAGNET GENERATOR IN THE NATURAL abc FRAME OF REFERENCE

A lumped parameter state model in the natural abc frame of reference for simulation and prediction of the transient performance of permanent magnet generators of the type depicted in Figure (1) and (2) was derived in a companion paper [1], and is restated in equation (1) for purposes of continuity.
Here, r_j represents the resistance of the jth winding, L_{jk} represents incremental self or mutual inductances. Here, j, k = a, b, c, kd, kq, sd, and sq, see Figure (1). In addition, e_a, e_b, and e_c are the induced back emfs, which represent the effect of the permanent magnet excitation system on the armature windings [1]. Here, one should also point out that the first term on the right hand side of equation (1) represents the ohmic voltage drop. Meanwhile, the third term represents the transformer voltage, and the combination of the second and last terms is the rotational voltage in this PM generator. This state model, which is developed in the natural abc frame of reference, was used as described in the following section to study the transient fault characteristics of the 75 KVA PM generator when it is subjected to a variety of faults. Notice that the machine winding inductances and emfs of this PM generator were determined as described and given in a companion paper, reference [1], and will not be repeated here for brevity.

COMPUTATION OF THE TRANSIENT FAULT CHARACTERISTICS OF THE PERMANENT MAGNET GENERATOR USING THE abc FRAME OF REFERENCE

Under transient conditions, such as the on-set of faults at the generator terminals or sudden changes in load, transient currents may exist in all of the machine windings including the damping circuits of the rotor, Figures (1) and (2). The stator mmfs and flux linkages can no longer be represented as uniformly rotating waveforms whose amplitudes are constant and whose rotation speed equals that of the rotor of the PM generator. Accordingly, the rotor circuits flux linkages are no longer constant and independent of time, and consequently induced currents exist in these rotor damping circuits. As a result, the seven differential equations given in the state model, equation (1), should be numerically solved simultaneously, when simulating the transients which follow the on-set of faults at the terminals of this PM generator. Solving such differential equations in the abc frame of reference, with full (nonsparse) and time dependent inductance matrices was considered until recent stages an ill-advised and very difficult task. However, due to advancements in numerical methods and development of very powerful computers, direct solution in the natural abc frame of reference of such machine equations became feasible and was carried out successfully in this work. Accordingly, the fault analysis of this 75 KVA PM generator was performed entirely in the natural abc frame of reference.

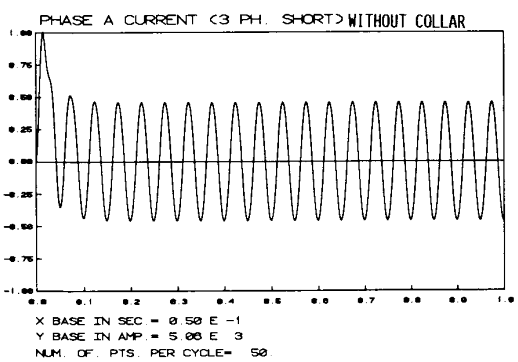
In this section and the following section, the PM generator's transient fault analysis was carried out assuming that the PM rotor's damping ring (collar) is nonexistant. That is the PM generator was designed without a rotor damping ring, and only damper bars equivalent circuits, kd and kq, were included in the model. Accordingly, the state model of equation (1) was reduced to a fifth order state model. However, the transient fault analysis was performed in a later section of this paper including the PM generator's rotor damping ring (collar).

Short Circuit Transient Starting From No-Load Condition - Three Phase to Neutral

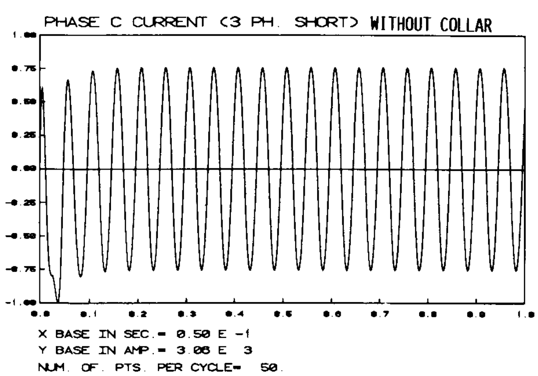
In order to perform a three phase transient fault analysis starting from no-load, the machine parameters were determined at no-load from the combined use of current-energy perturbation and finite element field solutions as described in a companion paper [1]. These parameters were used in the fifth order abc frame state model (without collar), to simulate a sudden three phase short circuit at the PM generator terminals. A fourth order Runge-Kutta numerical solution method was used to solve for the state variables (currents) in time. The resulting CSPs for the armature currents, i_a, i_b, and i_c, the damper bars' direct axis current, i_{kd}, and quadrature axis current, i_{kq}, were obtained and are given here in Figures (3) through (7), respectively.

$$
\begin{bmatrix} v_a \\ v_b \\ v_c \\ v_{kd} \\ v_{kq} \\ v_{sd} \\ v_{sq} \end{bmatrix}
=
\begin{bmatrix}
r_a & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & r_b & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & r_c & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & r_{kd} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & r_{kq} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & r_{sd} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & r_{sq}
\end{bmatrix}
\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_{kd} \\ i_{kq} \\ i_{sd} \\ i_{sq} \end{bmatrix}
+ \omega \left\{ \frac{d}{d\theta}
\begin{bmatrix}
L_{aa} & L_{ab} & L_{ac} & L_{akd} & L_{akq} & L_{asd} & L_{asq} \\
L_{ba} & L_{bb} & L_{bc} & L_{bkd} & L_{bkq} & L_{bsd} & L_{bsq} \\
L_{ca} & L_{cb} & L_{cc} & L_{ckd} & L_{ckq} & L_{csd} & L_{csq} \\
L_{kda} & L_{kdb} & L_{kdc} & L_{kdkd} & L_{kdkq} & L_{kdsd} & L_{kdsq} \\
L_{kqa} & L_{kqb} & L_{kqc} & L_{kqkd} & L_{kqkq} & L_{kqsd} & L_{kqsq} \\
L_{sda} & L_{sdb} & L_{sdc} & L_{sdkd} & L_{sdkq} & L_{sdsd} & L_{sdsq} \\
L_{sqa} & L_{sqb} & L_{sqc} & L_{sqkd} & L_{sqkq} & L_{sqsd} & L_{sqsq}
\end{bmatrix} \right\}
\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_{kd} \\ i_{kq} \\ i_{sd} \\ i_{sq} \end{bmatrix}
$$

$$
+
\begin{bmatrix}
L_{aa} & L_{ab} & L_{ac} & L_{akd} & L_{akq} & L_{asd} & L_{asq} \\
L_{ba} & L_{bb} & L_{bc} & L_{bkd} & L_{bkq} & L_{bsd} & L_{bsq} \\
L_{ca} & L_{cb} & L_{cc} & L_{ckd} & L_{ckq} & L_{csd} & L_{csq} \\
L_{kda} & L_{kdb} & L_{kdc} & L_{kdkd} & L_{kdkq} & L_{kdsd} & L_{kdsq} \\
L_{kqa} & L_{kqb} & L_{kqc} & L_{kqkd} & L_{kqkq} & L_{kqsd} & L_{kqsq} \\
L_{sda} & L_{sdb} & L_{sdc} & L_{sdkd} & L_{sdkq} & L_{sdsd} & L_{sdsq} \\
L_{sqa} & L_{sqb} & L_{sqc} & L_{sqkd} & L_{sqkq} & L_{sqsd} & L_{sqsq}
\end{bmatrix}
\cdot \frac{d}{dt}
\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_{kd} \\ i_{kq} \\ i_{sd} \\ i_{sq} \end{bmatrix}
+
\begin{bmatrix} e_a \\ e_b \\ e_c \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\qquad (1)
$$



PHASE (A) CURRENT DUE TO A 3-PHASE FAULT STARTING FROM NO-LOAD
Figure (3)



PHASE (C) CURRENT DUE TO A 3-PHASE FAULT STARTING FROM NO-LOAD
Figure (4)

A close look at each of these CSPs, reveals that the steady state was reached after a period of less than 10 cycles. This is expected for a PM generator of the type at hand, in which the rotor excitation is constant (the equivalent fictitious field current is constant), and no transient component of current associated with the excitation exists [1]. Furthermore, as can be seen from the CSPs of the armature currents, the profiles are not symmetrical about the zero current axis. Each profile includes as

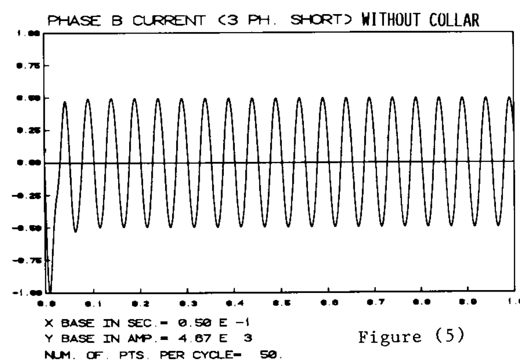
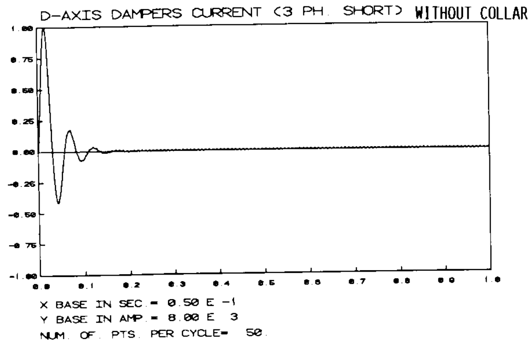


Figure (5)

PHASE (B) CURRENT DUE TO A 3-PHASE FAULT STARTING FROM NO-LOAD

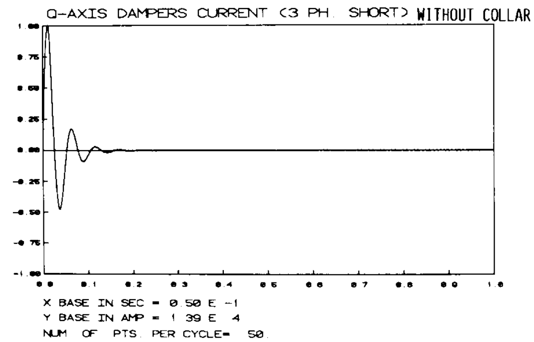
expected a dc component which is resulting from the fact that the flux linkages of these phase windings cannot change value instantaneously. A method to extract the value of the time constant of the dc component, T_a, as well as other time constants from these CSPs is given in one of the following sections.

In order to determine the transient current in each of the fourteen damper bars, Figure (2), the instantaneous values of i_{kd} and i_{kq}, at the end of each integration time step, were used. The current in each damper bar was determined as the result of superposition of the kd and kq contributions from i_{kd} and i_{kq}, respectively. Accordingly, the kd contributions to the currents in the damper bars, embedded in the pole faces, were distributed first from a sinusoidal waveform whose magnitude is equal to the instantaneous value of i_{kd}, at the end of each integration time step. In this case, the kd current waveform (distribution) is a sinusoidal one which peaks along the direct axis. Similarily, the kq contributions to the damper bar currents were distributed from another sinusoidal waveform (distribution) whose magnitude is equal to the instantaneous value of i_{kq}, at the end of each integration time step. In this case, the kq sinusoidal waveform peaks along the quadrature axis. For full details reference [7] should be consulted. This process of distributing the currents in the fourteen damper bars was repeated for all integration time steps in a transient fault solution. Figure (8) shows the resulting transient current, due to a sudden three phase fault, in bar #1.



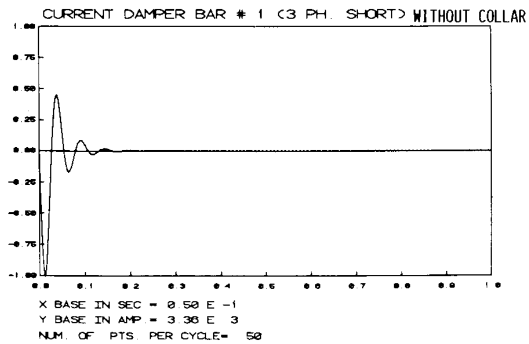
D-AXIS DAMPERS CURRENT DUE TO A 3-PHASE FAULT STARTING FROM NO-LOAD

Figure (6)



Q-AXIS DAMPER CURRENT DUE TO A 3-PHASE FAULT STARTING FROM NO-LOAD

Figure (7)



DAMPER BAR #1 CURRENT DUE TO A 3-PHASE FAULT STARTING FROM NO-LOAD

Figure (8)

Short Circuit Transient from 1.0 p.u. and 2.0 p.u. Load Conditions - Three Phase to Neutral

In order to study the transient characteristics of the PM generator when the on-set of a three phase fault takes place while the machine is operating under load condition, the above analysis was repeated at 1.0 p.u. and 2.0 p.u. loads. Here again, the fifth order state model was used (without collar). The state model inductance expressions, corresponding to 1.0 p.u. and 2.0 p.u. loads, were previously determined in reference [1] from finite element field solutions. These inductances were used for simulation of the transient faults responses starting from 1.0 p.u. and 2.0 p.u. load conditions, respectively. Accordingly, the CSPs of the transient currents in the five machine windings, a, b, c, kd and kq, were obtained. However, in the interest of brevity, only the CSPs of the phase (a) current are given here, for the 1.0 p.u. and 2.0 p.u. load cases, in Figures (9) and (10), respectively. The CSPs of the other currents i_b, i_c, i_{kd} and i_{kq} for these cases are given in reference [7] for interested readers. A comparison between these CSPs, with that obtained for i_a, at no-load, Figure (3), reveals considerable similarity in shape. However, the transient current peak value, given in these Figures, was decreased as the load was increased. This can be attributed to the demagnetizing effect of the armature reaction resulting from the loading effect in such permanent magnet machines. This is accentuated by the fact that in this type of PM generators, the rotor excitation is constant, and no field winding regulation exists.

Short Circuit Transient - Line to Line

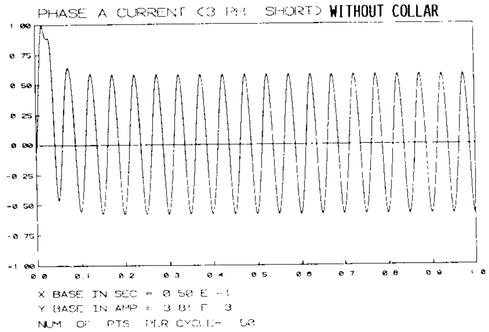
In order to perform a line to line (L-L) transient fault analysis starting from no load, a reduced third order state model was used, because in this case $i_a = -i_b$ and $i_c = 0$. Again, as in the two previous cases, currents in the mounted damping ring (collar) were not included, hence the model reduction process starts from a fifth order state model. Accordingly, the resulting state model becomes:

For full details on the derivation of this state model reference [7] should be consulted. The on set of the line to line short circuit was first assumed to have taken place while the PM generator was operating under no-load condition. The initial conditions and machine winding inductances were accordingly set. Accordingly, the CSPs of the (L-L) current, i_{LL}, the equivalent damper bars' direct-axis current, i_{kd}, and the equivalent damper bars' quadrature-axis current, i_{kq}, were obtained and are given here in Figures (11) through (13), respectively. As can be observed from Figures (12) and (13), the damper bars have a sustained (steady state) current of non zero value, as expected from the physical nature of the resulting stator mmf. This is due to the unbalanced condition which exists during a (L-L) fault, that leads to a stator mmf which no longer rotates at the same speed of the rotor.

Furthermore, in order to study the transient characteristics of the PM generator when a line to line fault starts from a load condition, the above analysis was repeated at 1.0 p.u. and 2.0 p.u. loads. This was accomplished by proper readjustment of the PM generator inductances and initial conditions according to these loads for use in the third order state model, equation (2). Again, the inductances of the PM generator windings corresponding to the 1.0 and 2.0 p.u. loads are given in references [1] and [7]. Here

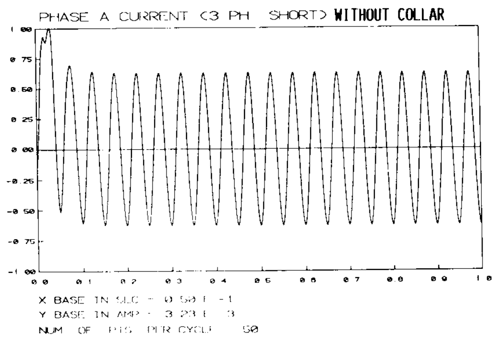
$$\begin{bmatrix} v_{LL} \\ v_{kd} \\ v_{kq} \end{bmatrix} = \left\{ \begin{bmatrix} r_a+r_b & 0 & 0 \\ 0 & r_{kd} & 0 \\ 0 & 0 & r_{kq} \end{bmatrix} + \omega \frac{d}{d\theta} \begin{bmatrix} (L_{aa}-2L_{ab}+L_{bb}) & (L_{akd}-L_{bkd}) & (L_{akq}-L_{bkq}) \\ (L_{kda}-L_{kdb}) & (L_{kdkd}) & (L_{kdkq}) \\ (L_{kqa}-L_{kqb}) & (L_{kqkd}) & (L_{kqkq}) \end{bmatrix} \right\} \begin{bmatrix} i_{LL} \\ i_{kd} \\ i_{kq} \end{bmatrix}$$

$$+ \begin{bmatrix} (L_{aa}-2L_{ab}+L_{bb}) & (L_{akd}-L_{bkd}) & (L_{akq}-L_{bkq}) \\ (L_{kda}-L_{kdb}) & (L_{kdkd}) & (L_{kdkq}) \\ (L_{kqa}-L_{kqb}) & (L_{kqkd}) & (L_{kqkq}) \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{LL} \\ i_{kd} \\ i_{kq} \end{bmatrix} + \begin{bmatrix} e_a-e_b \\ 0 \\ 0 \end{bmatrix} \quad (2)$$



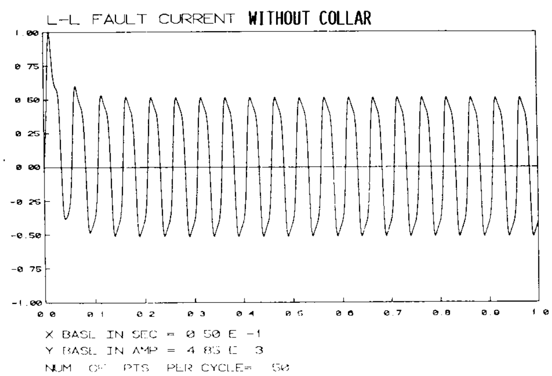
PHASE (A) CURRENT DUE TO A 3-PHASE FAULT STARTING FROM 1.0 P.U.-LOAD

Figure(9)



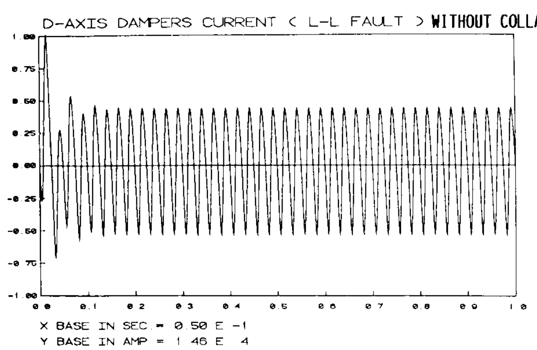
PHASE (A) CURRENT DUE TO A 3-PHASE FAULT STARTING FROM 2.0 P.U.-LOAD

Figure(10)



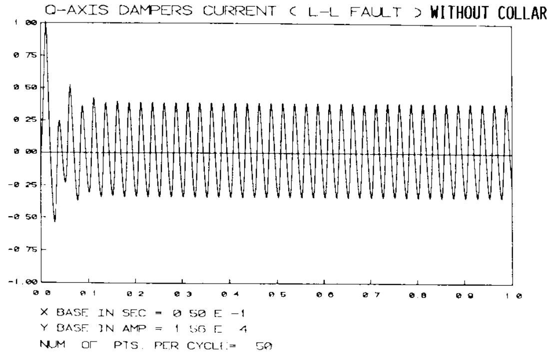
(L-L) FAULT CURRENT STARTING FROM NO-LOAD

Figure(11)



D-AXIS CURRENT DUE TO (L-L) FAULT STARTING FROM NO-LOAD

Figure(12)

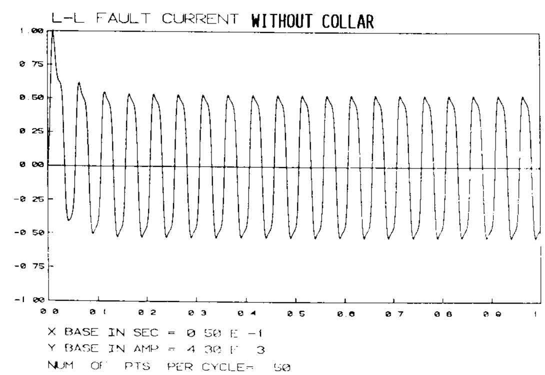


Q-AXIS CURRENT DUE TO (L-L) FAULT STARTING FROM NO-LOAD

Figure(13)

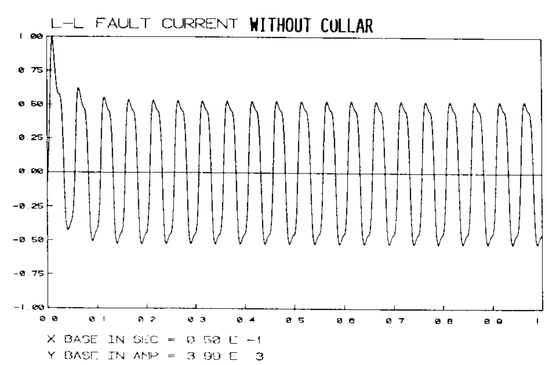
again, in the interest of brevity, only CSPs of the (L-L) fault current, i_{LL}, are given for the 1.0 p.u. and 2.0 p.u. load cases, in Figures (14) and (15), respectively. A comparison between these two CSPs and that obtained earlier for i_{LL}, at no-load, Figure (17), reveals substantial similarity in the current profiles. However, the loading effect is clear in progressively decreasing the resulting current peak values as the load increases. For further details on the above simulations as well as other simulations, consult reference [7].

In light of the above results, it can clearly be seen that the analysis of electric machines can be carried out completely in the abc frame of reference, without resorting to use of dq0 transformation and its resulting state models. Again, the nature of the parameters used in such abc frame model such as the



(L-L) FAULT CURRENT STARTING FROM 1.0 P.U.-LOAD

Figure(14)



(L-L) FAULT CURRENT STARTING FROM 2.0 P.U.-LOAD

Figure(15)

machine inductances and emfs, insure that one rigorously accounts for magnetic nonlinearities, space harmonics in the flux density waveforms and associated winding flux linkages. As stated earlier, these are all aspects which are lacking in conventional dq0 models. However, as can be seen from the published literature as pointed out in the introduction, the idea of using dq0 frame of reference is well embedded and used extensively when studying the performance of electric machinery. Accordingly, this work was extended to obtain the characteristic parameters of the PM generator in the dq0 frame of reference, such as the direct and quadrature axes steady state and subtransient inductances, and time constants. This was done with a view of accomodating those investigators with more of a systems interest that may wish to have access to such data.

COMPUTATION OF DIRECT AND QUADRATURE AXIS STEADY STATE AND SUBTRANSIENT INDUCTANCES AND TIME CONSTANTS USING THE STATE MODEL AND METHODS OF ANALYSIS OF IEEE STANDARD 115

It is often the conventional practice to use laboratory (shop floor) obtained oscillograms of short circuit currents of rotating machinery for determination of parameters of such machines, inductances (reactances) and time constants. An example of such methods is the techniques given in IEEE Standard 115 for determination of direct and quadrature axis inductances and time constants [6]. In this section the techniques recommended in IEEE 115 were applied here to the computer simulated transient short circuit current profiles in lieu of oscillograms of short circuit tests to determine d and q inductances and time constants, for the 75 KVA, 24000 r/min, two-pole PM generator at hand. That is, the techniques of IEEE Standard 115 were applied to the CSPs of the various cases given above to obtain the various d-q parameters. While steady state and subtransient inductances can be obtained for this PM generator, in the absence of an electromagnet type of field excitation, no transient inductances can be defined for this type of machine [8].

Figures (3) through (5) above represent the CSPs of the armature currents i_a, i_b, and i_c, respectively, following the on-set of a three phase short circuit at the terminals of the 75 KVA PM generator. The amplitude of the ac component of each of these current profiles can be given as a function of time, t, as follows [6,8]:

$$I_{ac}(t) = E/x_d + (E/x_d' - E/x_d)e^{-t/T_d'} + (E/x_d'' - E/x_d')e^{-t/T_d''} \qquad (3)$$

where E is the ac voltage before short circuit or the voltage computed from air-gap line of a saturated machine [8]. Here also, x_d, x_d', and x_d'' are the direct axis synchronous, transient and subtransient reactances, respectively. Furthermore, T_d' and T_d'' are the transient and subtransient time constants, respectively. Consider the right hand side of equation (3). Here, the first term, E/x_d, represents I_s, the sustained short circuit current value. Also, the term $(E/x_d'-E/x_d)$ represents the amplitude of the transient component, I_o'. Furthermore, the term, $(E/x_d''-E/x_d')$, represents I_o'', the amplitude of the subtransient component. Accordingly, equation (3) can be rewritten as follows [8]:

$$I_{ac}(t) = I_s + I_o' e^{-t/T_d'} + I_o'' e^{-t/T_d''} \qquad (4)$$

The direct-axis synchronous reactance, x_d, can be obtained according to IEEE Standard 115 methods [6] by performing "open-circuit saturation test" and "short-circuit saturation test," which require variations of the magnitude of field excitation. However, this procedure cannot be applied in this work which deals with permanent magnet (PM) generators with constant excitation (permanent magnet field). Accordingly, the direct-axis synchronous reactance, x_d, was obtained from CSPs of the sudden three phase short circuit armature currents by determination of the quotient of the open circuit line to neutral voltage, E, and the sustained short circuit armature current, I_s, as given below [8]:

$$x_d = E/I_s \qquad (5)$$

Here, I_s was taken, according to the standard practice [6], as the average of the three sustained armature currents, and, E, is the ac voltage before short circuit, which was computed from finite element field solutions as demonstrated by a companion paper [1]. Thus the direct axis synchronous inductance, $L_d = x_d/\omega$, where ω is the synchronous angular speed in rad/s. The resulting value of L_d for the PM generator at hand (without damping ring), when the on-set of the three phase short was assumed to have taken place under no-load condition, is given in Table (1) below.

As explained earlier, because of the constant field excitation of this type of PM generators, no transient component exists in the machine currents, Figures (3) through (8). Accordingly, the transient component, I_o', of equation (4) does not exist, and one can state that $I_o' = E/x_d'-E/x_d = 0$. Therefore in this case $x_d' = x_d$. Accordingly, equation (3) reduces to the following form:

$$I_{ac}(t) = E/x_d + (E/x_d'' - E/x_d)e^{-t/T_d''} \qquad (6)$$

Since E/x_d represents the amplitude of the sustained (steady state) short circuit current, I_s, one can subtract I_s from I_{ac} to obtain the magnitude of the ac subtransient component of a phase current, $I_{ac}''(t)$, as follows:

$$I_{ac}''(t) = (E/x_d'' - E/x_d)e^{-t/T_d''} \qquad (7)$$

Accordingly, the data defining the amplitude of the subtransient ac component in the CSP of each of the three phase currents, i_a, i_b, and i_c, Figures (3) through (5), was obtained. The three sets of data obtained from the i_a, i_b and i_c profiles were averaged, and the resulting data was curve fitted to the expression shown in equation (7) above. This was accomplished using commonly available software for curve fitting and signal processing [9], which minimizes the numerical error of a generated curve fit. Accordingly, the values of x_d'' and T_d'' were obtained using equation (7) in conjunction with the above mentioned curve fitting technique. The direct-axis subtransient inductance, is readily available as $L_d'' = x_d''/\omega$. The values of L_d'' and T_d'' based on the on-set of a three phase short circuit taking place under no-load are given in Table (1).

On the other hand, the quadrature-axis syncnronous inductance, L_q, can be determined, according to IEEE Standard 115 methods [6], by using the "slip test method" and other methods, which are not readily applicable in conjunction with the type of PM generators under consideration. Accordingly, the quadrature-axis sychronous inductance, L_q, was determined using two alternative methods. The first method makes use of abc armature inductance data in conjunction with classical expressions as detailed in a companion paper [1]. The second method makes use of flux plots resulting from magnetic field solutions in conjunction with phasor concept [10]. The details are given in a following section.

The next step was the computation of the quadrature-axis subtransient inductance, L_q''. The value of L_q'' at no load was obtained using the "sudden short circuit method" of IEEE 115. This procedure required the use of a three phase sudden short circuit simulation data, Figures (3) through (5), and a sudden line to line (L-L) short circuit simulation data, Figure (11). The ac subtransient component of the (L-L) fault current, i_{LL}, can be expressed as follows:

$$I''_{LL}(t) = I_{MLL}\, e^{-t/T''_{LL}} \quad (8)$$

where $I_{MLL} = I''_{LL}(0)$ and T''_{LL} is the (L-L) subtransient time constant [11]. The data corresponding to the amplitude of the ac subtransient component of the CSP of the (L-L) fault current, i_{LL}, Figure (11), was curve fitted to the expression shown in equation (8) above. This was done again with commonly available software, see reference [9]. Accordingly, the values of I_{MLL} and T''_{LL} were obtained. Next, following the procedure of IEEE Standard 115 "Sudden Short Circuit Method", [6], one can define the following:

$$I'' = I''_{LL}(t=0) + I_s \quad (9)$$

where I_s is the amplitude of the sustained (steady state) component of i_{LL}, from which the reactance x_{LL}, can be expressed as:

$$x_{LL} = \sqrt{3}\, E/I'' \quad (10)$$

where E is the open circuit voltage value before the on-set of the short circuit. This voltage E was computed here from finite element field solutions [1]. Accordingly, the quadrature-axis subtransient reactance, x''_q, can be computed as follows [6]:

$$x''_q = (x_{LL} - x''_d)^2 / x''_d \quad (11)$$

where x''_d is the direct-axis subtransient reactance obtained earlier from three phase fault simulations. From which the quadrature-axis subtransient inductance becomes $L''_q = x''_q/\omega$. The values of L''_q and T''_{LL}, at no load, are given in Table (1).

Table (1)

Damper Bars Only			
	No Load	1pu Load	2pu Load
L_d μH (p.u.)	41.429 (.181)	43.393 (.189)	47.417 (.207)
L''_d μH (p.u.)	14.756 (.064)	19.856 (.087)	22.921 (.100)
L''_q μH (p.u.)	31.261 (.136)	22.592 (.099)	21.9 (.096)
T''_d ms	0.794	0.877	1.002
T''_{LL} ms	1.379	1.496	1.648
T_a ms	3.242	1.659	1.301

MACHINE INDUCTANCES AND TIME CONSTANTS FROM COMBINED STATE MODEL AND IEEE STD. 115 METHODS CASE WITHOUT DAMPING COLLAR

Finally, the CSPs of the transient currents, Figures (3) through (5), which represent the armature currents due to a sudden three phase short circuit starting from no-load, were used to determine the dc time constant, T_a. The numerical data corresponding to the amplitude of the dc component of the CSP of each of the three phase currents, Figures (3) through (5), was obtained. The three sets of data were averaged, and the resulting data was curve fitted, using the above mentioned curve fitting and signal processing software [9] to the following expression:

$$I_{dc}(t) = I_{dco}\, e^{-t/T_a} \quad (12)$$

where I_{dco} is the initial value of I_{dc}, that is at t = 0, and T_a is the dc time constant. The resulting value of T_a at no-load is given in Table (1). In the next section the effect of armature load on the above PM generator parameters is determined.

EFFECT OF LOAD ON MACHINE PARAMETERS

In order to determine the effects of armature currents (load) on the different machine parameters, the same process, of obtaining the direct-axis and quadrature-axis synchronous and subtransient inductances and time constants, detailed above, was repeated for 1.0 p.u. and 2.0 p.u. loads. Here, CSPs of the transient armature currents, following the on-set of a three phase as well as line to line (L-L) short circuit, starting from an operating condition for the 75 KVA PM generator of 1.0 p.u. and 2.0 p.u. loads, were used for the determination of the parameters of the machine. The results of the 1.0 p.u. and 2.0 p.u. cases are given in Table (1), in addition to the no-load case values for purposes of comparison. For full details reference [7] should be consulted.

As can be seen from Table (1), armature loading had a significant impact on the values of the PM generator parameters in comparison to their corresponding values determined from no-load initial conditions. Upon examination of the direct axis parameters, the direct-axis synchronous inductance, L_d, and the direct-axis subtransient inductance, L''_d, the values of these inductances increased with the application of load (armature currents). This can be explained, by the fact that the armature loading (armature reaction) demagnetizes the magnetic circuit (opposes permanent magnet flux) along the direct-axis and hence helps lowering the flux densities opposite the direct axis. Hence, an increase in direct axis "effective permeance" takes place due to load. Accordingly, the direct-axis synchronous and subtransient inductances, L_d and L''_d, increase in value (both are proportional to permeance) due to the armature load (armature reaction).

On the other hand, if one considers the quadrature-axis subtransient inductance, L''_q, the values of this inductance decreased with the application of load. This inductance is related more to the reaction of the damper windings to armature load. Furthermore, if one consider direct-axis subtransient time constant, T''_d, the value of this time constant was increased as the load increased.

To check the validity of these values, one can substitute the values of L_d, L''_d, and T''_d, corresponding to a particular load condition, Table (1), into equation (6), of $I_{ac}(t)$, to obtain an expression for the magnitude of the ac component of an armature short circuit current, corresponding to that load condition. Since the values of L_d and L''_d increases with load, the corresponding magnitude of the ac current, $I_{ac}(t)$ decreases. This trend of decrease in the magnitude of the ac component of the armature short circuit currents as the load increases was observed (confirmed) earlier in the CSPs of the armature current obtained from the comprehensive state model of the PM generator at no load, 1.0 p.u. load and 2.0 p.u. load as shown in Figures (3), (9), and (10), respectively for the phase (a) current. This confirms the consistancy of the resulting parameters and gives rise to confidence in this method for obtaining the machine parameters. Further evidence will be given in the following section, where the inductance values are compared with values obtained from other methods of computation of direct and quadrature axis inductances.

COMPARISON BETWEEN INDUCTANCES COMPUTED FROM COMBINED USE OF THE STATE MODEL - METHODS OF IEEE STANDARD 115 AND THOSE OF OTHER METHODS OF COMPUTATION OF DIRECT AND QUADRATURE AXIS INDUCTANCES

The values of the direct-axis synchronous inductance, L_d, under different load conditions, obtained from combined use of the state model and methods of IEEE Standard 115, Table (1), are compared with values obtained from closed form and armature incremental inductance expressions. The details of obtaining values of L_d from closed form and inductance expressions are given in a companion paper [1]. Table (2) shows values of the inductance, L_d, under different load conditions as obtained from both methods for purposes of comparison. A reasonable agreement prevails for each of the no-load, 1.0 p.u. load, and the 2.0 p.u. load conditions. Furthermore, if one considers the values of L_d as obtained from either method, one observes the same trend of increase in the values of L_d as the load increases. Again, this can be attributed to the armature loading (armature reaction) effect which demagnetizes the machine's magnetic circuit as was explained above.

Furthermore, in this section, the quadrature-axis synchronous inductance values are given under different load conditions, Table (3), as were computed from two different methods. One method involves the use of armature inductance expressions obtained from finite element field solutions as detailed in a companion paper [1]. The second method makes use of flux plots resulting from magnetic field solutions and resulting torque angles under load [10]. This latter method will not be described here since it has been explained in detail by Demerdash and Hamilton in reference [10]. Here again, a good agreement exists between values corresponding to a particular load condition as obtained from both methods, Table (3). Furthermore, if one considers the values of L_q as obtained from either method, one observes the same trend of increase in the values of L_q as the load increases. This can also be attributed to magnetic circuit demagnetization under load, which was explained above.

Table (2)

L_d Inductance Under Different Load Conditions		
	State Model + IEEE STD 115 $\mu H(p.u.)$	Closed Form + Inductance Expressions $\mu H(p.u.)$
$L_d(No-Load)$	41.429 (.181)	46.686 (.204)
$L_d(1p.u-Load)$	43.393 (.189)	47.989 (.209)
$L_d(2p.u-Load)$	47.417 (.207)	49.249 (.215)

L_d INDUCTANCE VALUES UNDER DIFFERENT LOAD CONDITIONS AS OBTAINED FROM TWO METHODS CASE WITHOUT DAMPING COLLAR

Table (3)

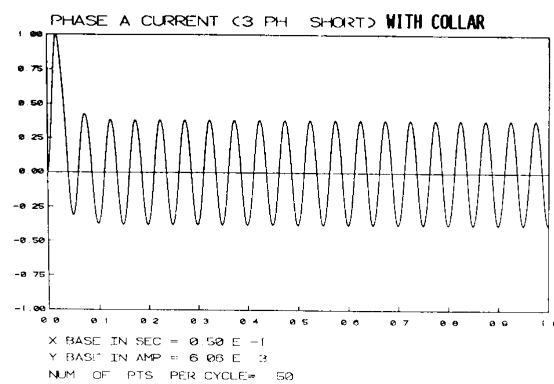
L_q Inductance Under Different Load Conditions		
	Flux Plots + Phasor Diagram $\mu H(p.u.)$	Closed Form + Inductance Expressions $\mu H(p.u.)$
$L_q(No-Load)$	N.A.	40.291 (.176)
$L_q(1p.u-Load)$	42.890 (.187)	42.727 (.186)
$L_q(2p.u-Load)$	45.846 (.200)	46.696 (.204)

L_q INDUCTANCE VALUES UNDER DIFFERENT LOAD CONDITIONS AS OBTAINED FROM TWO METHODS CASE WITHOUT DAMPING COLLAR

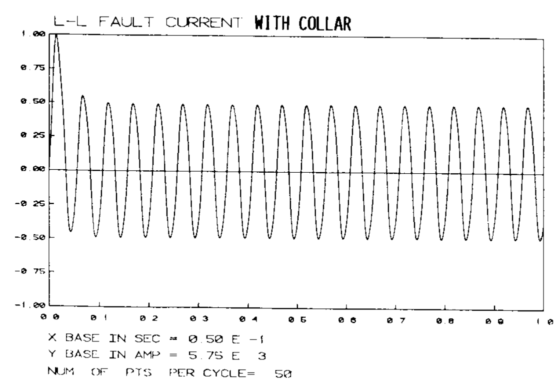
As was stated earlier in this paper, the analysis and determination of machine parameters were performed for the case when only damper bars exist in the machine, that is by excluding the possible presence of a damping ring (collar) in the PM generator design, Figures (1) and (2). The impact of addition of the shorted damping ring (collar) on generator parameters is studied in the following section.

IMPACT OF ADDITION OF A SHORTED DAMPING RING AROUND THE PERMANENT MAGNET ROTOR ON GENERATOR PARAMETERS

To study the impact of addition of a shorted damping ring (collar) around the permanent magnet rotor on generator parameters, the full state model, equation (1), was used to perform three phase transient short circuit analysis. Furthermore, for the (L-L) transient short circuit analysis case, the third order state model of equation (2) was modified to include the rotor-mounted damping ring (collar) which leads to a fifth order state model. Full details are given in reference [7]. Accordingly, the three phase and (L-L) short circuit fault analysis were performed at no-load, 1.0 p.u. load, and 2.0 p.u. load conditions, in much the same fashion as described earlier for the case without the ring. The various machine current CSPs were obtained, including those of the damping ring, corresponding to these load conditions. However, in the interest of brevity, only the CSP of the phase (a) current, i_a, following the on-set of a three phase short circuit starting from no-load, and line to line CSP of the transient current following the on-set of a line to line short circuit starting from no-load, are given here in Figures (16) and (17), respectively.



PHASE A CURRENT DUE TO A 3-PHASE FAULT STARTING FROM NO-LOAD CASE WITH DAMPING COLLAR
Figure(16)



(L-L) FAULT CURRENT STARTING FROM FROM NO-LOAD CASE WITH DAMPING COLLAR
Figure(17)

Consider these two CSPs of the transient currents, Figures (16) and (17), resulting from the case when the damping ring is included. Also consider their corresponding CSPs, obtained from analysis of the PM generator without damping ring, Figure (3) and Figure (11). Here, one can notice that the corresponding CSPs of the transient currents in both sets of Figures are of similar profiles. Furthermore, one can observe that the transient peak values (1st cycle) of i_a and i_{LL} were increased for the case when the damping ring was included. However, the transients, decayed at a faster rate for the case with the ring. This trend is consistant with expectations based on resulting stronger damping as detailed in a discussion given below.

On the other hand, the machine inductances and time constants which were computed earlier for the PM generator without the damping ring using the state models developed here in combination with IEEE Standard 115 methods, were computed again for the PM generator after the addition of the damping ring. The results corresponding to the no-load, 1.0 p.u. load, and 2.0 p.u. load are given in Table (4) below. Consider the values of the direct-axis synchronous inductance, L_d, as given in Table (1) for the case without the damping ring, and the corresponding values in Table (4) given for the case with the ring included. The values of L_d were changed by less than 1%. This was expected, since the damping circuits have more pronounced effect on the subtransient component of the ac current. This effect is clear here in the values of the direct-axis subtransient inductance, L''_d, the quadrature-axis subtransient inductance, L''_q, and the direct-axis subtransient time constant, T''_d. As can be observed from these parameters, Table (1) and Table (4), and from the CSPs of Figures (3), (11), (16), and (17), the addition of the damping ring caused an increase in the initial peak values of the transient currents. However, stronger damping of the current oscillations can be observed by the shortening of the duration of these transients (the transients decayed at a faster rate).

Table (4)

Damper Bars + Collar			
	No Load	1pu Load	2pu Load
L_d μH (p.u.)	41.477 (.181)	43.325 (.189)	47.204 (.206)
L''_d μH (p.u.)	9.312 (.041)	10.546 (.046)	13.625 (.060)
L''_q μH (p.u.)	24.188 (.106)	26.235 (.115)	29.681 (.130)
T''_d ms	0.736	0.744	.863
T''_{LL} ms	1.192	1.184	1.370
T_a ms	2.177	2.104	2.425

MACHINE INDUCTANCES AND TIME CONSTANTS FROM COMBINED STATE MODEL AND IEEE STD. 115 METHODS CASE WITH COLLAR INCLUDED

It is clear that the addition of the damping ring strengthens the overall rotor damping of the machine. This is because the shorted ring is in reality a second damping circuit dissipating energy, thus leading to a shorter transient period.

DISCUSSION OF THE ADVANTAGES OF THE NATURAL abc FRAME OF REFERENCE FOR MACHINE MODELING IN LIGHT OF RESULTS

Previous work dealing with the numerical analysis of magnetic fields in electrical machines was centered almost exclusively on the calculation of conventional d-q machine parameters such as the saturated values of direct and quadrature axis steady state, transient, and subtransient reactances. Such reactances are useful when the machine currents are pure sinusoids in the time domain, and the mmfs resulting from the distributed windings are sinusoidally distributed in space, in which case purely sinusoidal, uniformly rotating, flux waveforms are produced, and hence one can resort to a uniformly rotating dq0 frame of reference for machine modeling.

However, with the rapid increase in the use of generator systems with electronically switched loads (rectified loads), and motor drive systems with solid-state inverter control, the current waveforms necessary to supply such loads, and hence currents of generators supplying such loads are no longer pure sinusoids. These currents contain substantial content of harmonics. The effects of time domain harmonics in these current waveforms and the resulting space harmonics in the mmf waveforms, which consequently complicate the nature of the modeling process, necessitate that one should not neglect such harmonics in the analysis and in the processes of computer-aided prediction of the performance of such machine systems.

Before the advent of applying computer-aided numerical methods to the analysis of electric machinery, saturation and parameters nonlinearity were accounted for by empirical or semi empirical methods. Also, the equations of electrical machines were simplified by proper substitution (transformation) of variables and using transforms such as Park's transformation and the resulting dq0 frame and associated models. However, with advances in numerical techniques using computers, one can solve directly the set of differential equations resulting from modeling electrical machines in the natural abc frame of reference, as was shown above in this paper.

An advantage of using the natural abc frame modeling approach is that one can easily account for inherent harmonics in flux linkages and inductances. Another advantage is that the abc frame approach can be used easily to study internal or terminal faults resulting from abnormal winding connections as was demonstrated above. Furthermore, the method enables one to directly use readily available finite element based methods to determine the nonlinear self and mutual inductances of various machine windings from finite element field solutions, as was demonstrated in a companion paper [1]. These are the key parameters of the state models in the abc frame of reference, which were used in this paper. Also, the method makes it easier to compare simulated results with corresponding test data since most of the testing processes on electrical machines lead to measurements of a, b, and c phase and line currents and voltages.

Another important advantage of this approach, is that it makes it easier to incorporate such abc machine models into an overall modeling effort of the system network including inverter drives or rectifier loads which are inherently in the abc frame of reference. Using this approach eliminates the problem of interfacing such abc load and electronic power conditioning circuit models with a dq0 machine network model. Accordingly, the state model which was developed in a companion paper [1], and used in this paper, will be used in a future paper [12], in the study of the characteristics of this permanent magnet generator when feeding electronically switched dc (rectified) loads, as well as in studying the effects of electronic component failure in the associated rectifier bridge on the generator-rectifier-load system performance.

CONCLUSIONS

A computer-aided method to model transient characteristics of permanent magnet generators with multiple damping circuits was presented. The method is based on the use of state models in the natural abc frame of reference, with parameters determined from a combined energy-current perturbation technique and finite element field solutions. An advantage of this method over other methods that employ dq0 state models is that magnetic nonlinearities, space harmonics in flux density waveforms as well as in the mmfs are easily and readily accounted for. The method was applied to a two pole, 75 KVA, 208V, 24000 r/min permanent magnet generator with multiple damping circuits, to study the effects of various generator faults and loading effects on generator transient characteristics. Furthermore, the natural abc state models were applied in determination of synchronous and subtransient inductances and time constants. These inductances resulted from combined use of state models in the natural abc frame of reference and methods of IEEE Standard 115. These inductance data compared well with inductances computed from other methods of computation which gave validity to the present work. Furthermore, the impact of addition of a shorted ring (collar) around the permanent magnet rotor on the transient characteristics and parameters of the 75 KVA PM generator was studied. Finally, in light of the results obtained, the advantages of the natural abc frame of reference in modeling electric machines were highlighted and clarified. Further use of this modeling approach in analysis of permanent magnet generator-electronically rectified and conditioned loads will be reported on in future papers.

ACKNOWLEDGMENT

The authors wish to acknowledge that this work was partially funded by Sundstrand Corporation, Rockford, Illinois, under Contract No. PO B-2L34 93-247 with Clarkson University.

REFERENCES

[1] Arkadan, A. A., Demerdash, N. A. and Vaidya, J. G., "Impact of Load on Winding Inductances of Permanent Magnet Generators with Multiple Damping Circuits Using Energy Perturbation," A Companion Paper, Submitted for Review and Presentation at the IEEE-PES 1988 Winter Meeting, New York.

[2] Nehl, T. W., Fouad, F. A. and Demerdash, N. A., "Determination of Saturated Values of Rotating Machinery Incremental and Apparent Inductances by an Energy Perturbation Method," IEEE Transactions on Power Apparatus and Systems, PAS-101, 1982, pp. 4441-4451.

[3] Hannalla, A. Y., "Analysis of Transient Field Problems in Electrical Machines Allowing for End Leakage and External Reactances," IEEE Transactions on Magnetics, Vol. MAG-17, pp. 1240-1243, 1981.

[4] Rahman, M. A. and Little, T. A., "Dynamic Performance Analysis of Permanent Magnet Synchronous Motors," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, pp. 1277-1282, 1984.

[5] Amaratunga, G. A., Acarnley, P. P. and McLaren, P. G., "Optimum Magnetic Circuit Configurations for Permanent Magnet Aerospace Generators," IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-21, No. 2, March 1985, pp. 230-255.

[6] IEEE Guide: "Test Procedures for Synchronous Machines, IEEE Std. 115-1983, IEEE, Inc., 345 East 47th Street, New York, NY 10017, USA.

[7] Arkadan, A. A., "Computer-Aided Dynamic Performance Prediction of Permanent Magnet Generator Systems with Damping Circuits and Electronically Switched Loads," Ph.D. Dissertation, Clarkson University, Expected December 1987.

[8] Kimbark, E. W., Power System Stability: Synchronous Machines, New York, Dover Publications, Inc., 1968.

[9] "International Mathematical Statistical Library," "IMSL," Routine "ZXSSQ."

[10] Demerdash, N. A. and Hamilton, H. B., "A Simplified Approach to Determination of Saturated Synchronous Reactances of Large Turbogenerators Under Load," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-95, No. 2, March/April 1976, pp. 560-569.

[11] Adkins, B. and Harley, R. G., The General Theory of Alternating Current Machines: Application to Practical Problems, Chapman and Hall, London, 1975.

[12] Arkadan, A. A., Hijazi, T. M. and Demerdash, N. A., "Modeling of the Performance of a System of Electronically Rectified Load-Permanent Magnet Generator with Multiple Damping Circuits Using the Natural abc Frame of Reference," Paper Under Preparation, to be submitted for Review and Presentation at the IEEE-PES 1988 Summer Meeting.

A. A. ARKADAN (S79) was born in Sidon-Lebanon on June 1, 1956. He received his B.S. degree in Electrical Engineering with honors (Magna Cum Lauda) from the University of Mississippi in 1980. In August, 1981 he received his M.S. in Electrical Engineering from Virginia Polytechnic Institute and State University. During the period 1981-1984 he worked in industry as a design and quality control engineer in Saudi Arabia. A. A. Arkadan has been working towards his Ph.D. degree at Clarkson University since September 1984, where he is expected to complete the requirements for the Ph.D. degree in the Fall of 1987. During the Summers of 1985 and 1986 he worked in Aviation Operations at Sundstrand Corporation, Rockford, Illinois, where he developed software packages for modeling and analysis of generator-rectified load systems and motor-inverter drive systems. Mr. Arkadan's current interests include: finite element field analysis associated with machine systems, computer aided design and modeling of electronically operated machines including simulation of failure modes of electronic system components. Mr. Arkadan is a student member of IEEE, Phi Kappa Phi, Pi Mu Epsilon, Eta Kappa Nu, and Tau Beta Pi.

NABEEL A. DEMERDASH (M'85 - SM'74) was born in Cairo, Egypt, on April 26, 1943. He received the B.Sc. E.E. degree with distinction and first class honors from Cairo University, Egypt, in 1964 and the M.S. and Ph.D. degrees in Electrical Engineering from the University of Pittsburgh, Pittsburgh, Pennsylvania, in 1967 and 1971, respectively. In 1968 he joined the Large Rotating Apparatus Division of Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania, as a Development Engineer. From 1972 to 1983 Prof. Demerdash held the positions of Assistant Professor, Associate Professor and Professor in the Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. He is presently a professor in the Department of Electrical and Computer Engineering, Clarkson University, Potsdam, New York.

Prof. Demerdash's current interests and research activities include Electromechanical Propulsion and Actuation, Computer-Aided Modeling of Electronically Controlled Electrical Machinery and Drive Systems, Numerical Analysis of Electromagnetic Fields in Electrical and Electronic Devices, as well as Machine-Power Sytem Dynamics, and Power Electronics.